

# Multi-Kilowatt Power Module for High-Power Hall Thrusters

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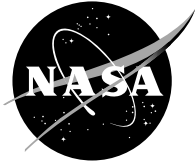
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**Future NASA missions will require high-performance electric propulsion systems. Hall thrusters are being developed at NASA Glenn for high-power, high-specific impulse operation. These thrusters operate at power levels up to 50 kW of power and discharge voltages in excess of 600 V. A parallel effort is being conducted to develop power electronics for these thrusters that push the technology beyond the 5 kW state-of-the-art power level. A 10 kW power module was designed to produce an output of 500 V and 20 A from a nominal 100 V input. Resistive load tests revealed efficiencies in excess of 96 percent. Load current share and phase synchronization circuits were designed and tested that will allow connecting multiple modules in parallel to process higher power.**

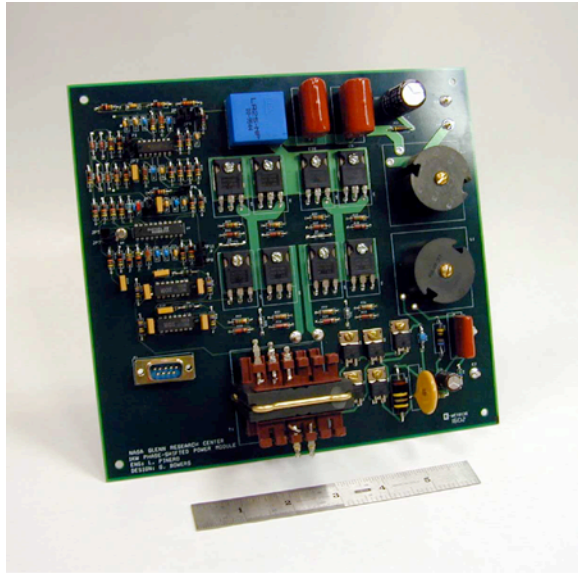
## I. Introduction

High-power electric propulsion (EP) has been identified as enabling for applications including human Mars missions.<sup>1</sup> Using a hybrid transportation mission strategy, including EP, cryogenics and aerobraking, the power requirement for the EP system is reduced to 0.5 to 1.0 MWe compared to all electric architectures. A possible implementation of this concept uses an array of 50 kW-class Hall effect thrusters (HET) like the NASA-457M.<sup>2</sup>

Direct-drive approaches using solar arrays or thermo-mechanical systems, that could reduce mass and improve efficiency of power processing units (PPUs), have been demonstrated.<sup>3-7</sup> However, these systems have several shortcomings including high voltage arcing, lack of regulation and plasma interactions between the HET and solar arrays. For applications where these problems can not be surmounted traditional PPUs with DC-DC converters are required.

PPUs for high power systems challenge current technology. High voltages and currents require special attention so that undesirable power losses and parasitic transients are not created. For high power applications, power can be processed in smaller fractions to reduce voltage and current magnitudes and allow the use of more efficient semiconductors. These power modules can be used as building blocks by connecting them in series or parallel to produce the desired voltages and currents.

Recently NASA Glenn Research Center (NASA GRC) developed a 1 kW power module for Hall thrusters, shown in Figure 1.<sup>8</sup> It consisted of a phase-shifted full-bridge converter operating at a switching frequency of 50 kHz. The module, operated with an input voltage of  $100 \pm 20$  V<sub>DC</sub>, generated a nominal output of 300 V<sub>DC</sub>. This module, integrated with a NASA-120Mv2 HET, demonstrated efficiencies in excess of 96 percent. The total component weight of this unit, including printed circuit boards, was 0.765 kg. The reason for developing this module was to create a test bed to evaluate circuits, concepts and designs that could be applied to a higher power module design.



**Figure 1. 1kW breadboard power module**

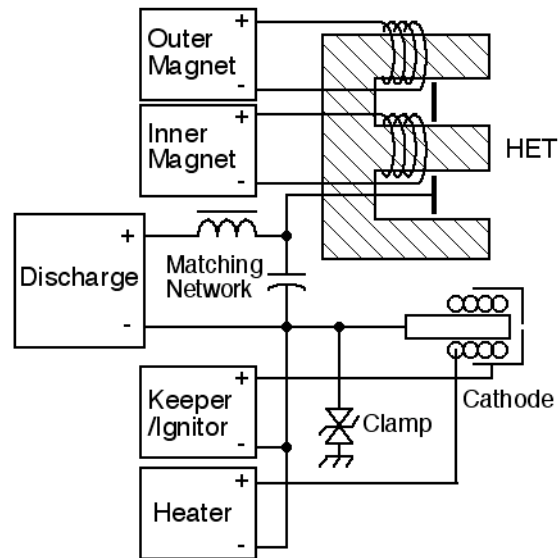
The 1 kW power module was not designed with circuitry to operate multiple modules in a parallel configuration. During this investigation, a load current share circuit was designed and implemented to force the output current to evenly divide between modules. Three 1 kW modules were connected in an arrangement with both inputs and outputs in parallel to increase current output. In addition, this parallel arrangement enabled the use of a phase-synchronization or phase-staggering circuit that shifted the switching phases of the modules reducing input and output ripples. Three 1 kW modules including these additional functions were used to assemble a 3 kW discharge power supply. This unit was successfully integrated with the NASA-120Mv2 HET.

All power and control design concepts implemented in the 1 kW module were then used to develop a multi-kilowatt power module. A power level of 10 kW was selected because of semiconductor parts and magnetic cores availability. This paper describes the design of the 10 kW power module and the 3 kW parallel architecture discharge supply and the results of resistive load and integration test with a HET.

## II. Thruster Interface and PPU Specifications

Figure 2 shows a typical block diagram of a HET PPU that includes five power supplies: the discharge, inner and outer magnet, cathode keeper and heater supplies. The largest converter is the discharge supply which processes up to 95 percent of the power into the thruster providing high voltage for accelerating ions by driving a nonlinear, dynamic plasma load that can exhibit large current oscillation and negative resistance characteristics. For these reasons, the design of an optimized discharge supply is paramount to the development of a highly efficient and reliable HET PPU.

The nominal input voltage selected for the 10 kW power module was 100 V. This voltage is compatible with existing high-power solar-based power systems.<sup>9</sup> In the case of nuclear-based thermo-mechanical power systems, AC bus voltage magnitude is determined by the alternator design. A trade study would be required to determine if a 100 V bus is advantageous for a specific application depending on total power level and spacecraft size.<sup>10</sup> From a PPU perspective, this voltage is advantageous because it allows using of low voltage metal oxide semiconductor field effect transistors (MOSFET) that have low on-resistance and can potentially yield higher efficiency. This is because the on-resistance of power MOSFETs increases rapidly with the voltage handling capability making it difficult to design high efficiency, high voltage converters. This effect is more important for applications with high radiation environments because radiation hardened MOSFETs have even higher on-resistance than standard parts. An output voltage of 500 V was chosen because HETs like the NASA-457M and the NASA-173M are designed to operate at higher specific impulse requiring higher discharge voltages.<sup>2,11-12</sup>



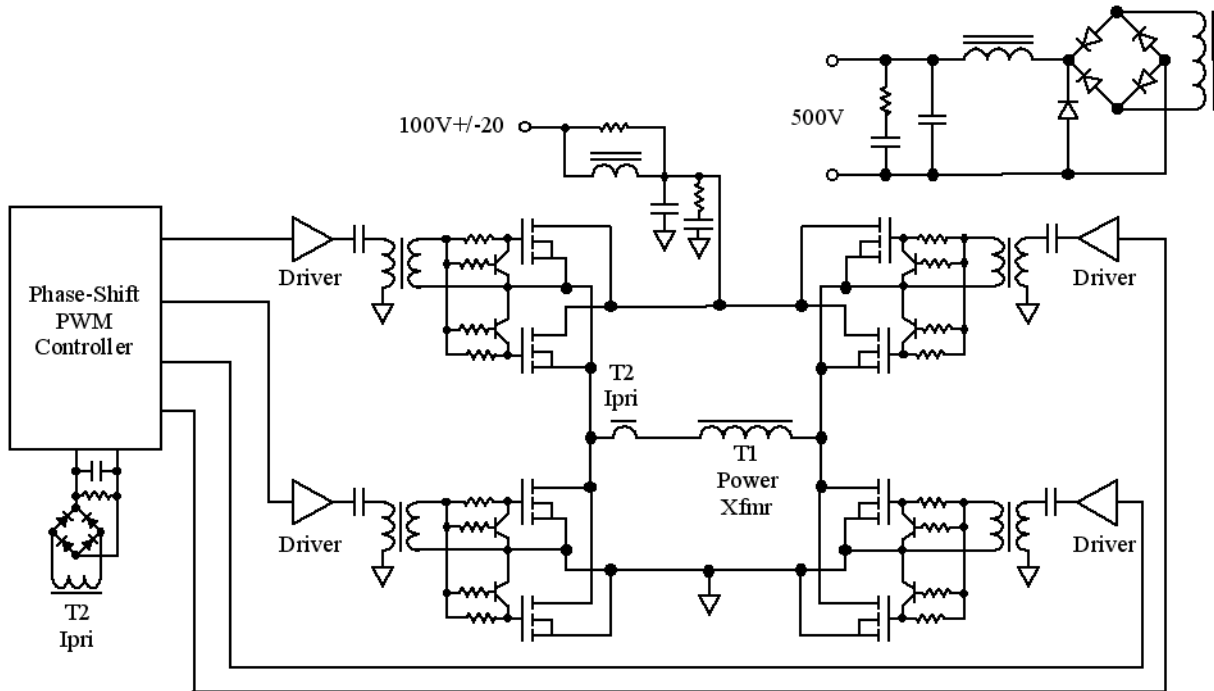
**Figure 2. Block Diagram of typical Hall thruster electrical connections**

## III. Multi-kilowatt Power Module

### A. Design

Inefficiencies in high-frequency DC-DC converters are due to conduction and switching losses on power semiconductors, such as MOSFETs and rectifier diodes, and core losses on the magnetic components such as the

power transformer and filter inductors. Conduction losses are affected by component equivalent resistances and current levels in the module. These can be minimized by using high-performance semiconductors or paralleling parts. Switching losses are caused by turning on and off transistors and rectifier diodes. These losses can be minimized by decreasing switching speed or implementing zero-voltage switching techniques like those used in resonant and pseudo-resonant converters. Regardless of the approach implemented, switching losses are proportional to the switching frequency.<sup>13</sup> Core losses, which are particular for each core material, are also proportional to the switching frequency and the magnetic flux density in the magnetic core. The design of the 10 kW power module attempted to minimize these losses to obtain maximum efficiency with a minimum parts count.



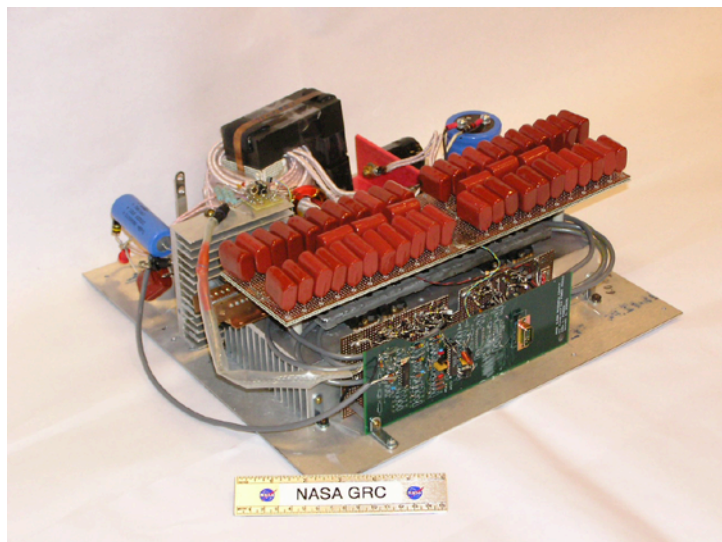
**Figure 3. Simplified schematic of 10 kW power module**

The topology used for the 10 kW module was a phase-shifted full-bridge converter. A simplified circuit schematic is shown in Figure 3. Three significant design changes had to be implemented relative to the 1 kW design because of the higher power level on this application. First, the switching frequency was decreased from 50 kHz to 20 kHz to reduce switching losses. Second, the power stage that routes input current through the MOSFETs and the transformer was designed to minimize interconnections, current path length and loop inductance. These can introduce parasitic elements to the power circuit resulting in transients detrimental to the performance of a converter. Snubbers are then required to damp these transients at the cost of further power losses. The power stage also included larger heat sinks for improved heat rejection. Third, the gate drive circuit design was changed from a charge-pump based circuit to a transformer-isolated design with high current drivers. This was implemented because the larger gate capacitance in high power transistors requires high current for fast and efficient switching. The bipolar drive from the transformer-isolated design improves turn-off characteristics. In addition, a “Miller killer” circuit, using a bipolar junction transistor, was added to minimize the effect of the Miller capacitance on the MOSFETs and further increase turn-off speed.

Other changes were made to improve efficiency. Two high-power MOSFETs, in an SOT-227 package and with very low on-resistance, were used on each leg of the bridge converter. Also, high-voltage, high-current, ultra-fast, soft-recovery diodes, in a TO-247 packages, were used for the output rectifier. These allowed the use of one single bridge rectification output stage, which minimizes losses and simplifying transformer design. Last, a new high power transformer was assembled by stacking two large ferrite C-cores. The windings utilized an interleaved design, a minimum number of layers and Litz wire to minimize leakage inductance and proximity and skin effects.

As in the 1 kW module design, phase-shifted, peak-current-mode, pulse-width-modulation (PWM) control was implemented using a commercially available integrated circuit (IC). This device included all the necessary

functions including the four phase-shifted gate drives, current limit and soft-start. Integrating this IC into the design resulted in a significant part count reduction. The component weight of the 10 kW power module is 6.2 kg without including heat sinks or mounting hardware. A photograph of the breadboard is shown in Figure 4.



**Figure 4. Multi-kilowatt breadboard power module**

#### B. Resistive Load Test

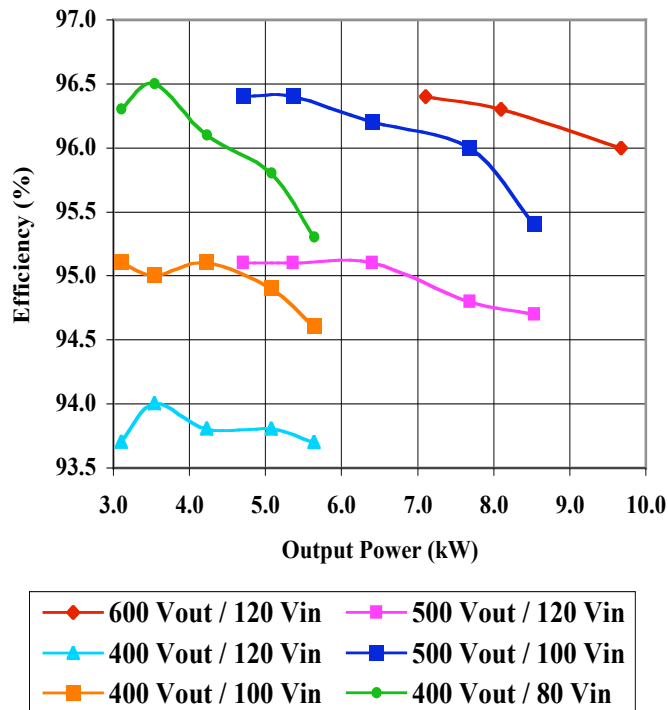
The performance of the multi-kilowatt power module was tested using a resistive load. Testing included verification of input and output characteristics like voltage, current, ripple and efficiency. Figure 5 shows a graph of total electrical efficiency as a function of output power for various voltages. Efficiencies greater than 96 percent were obtained through a wide range of output powers. These data include housekeeping power. Efficiency measurements were taken after the breadboard module reached thermal equilibrium. These efficiencies were attributed to the soft-switching characteristics of the phase-shift bridge converter, fast gate drive circuits and low parasitics losses inherent in the design.

### IV. Modular Architectures

#### A. Load Current Sharing Circuit

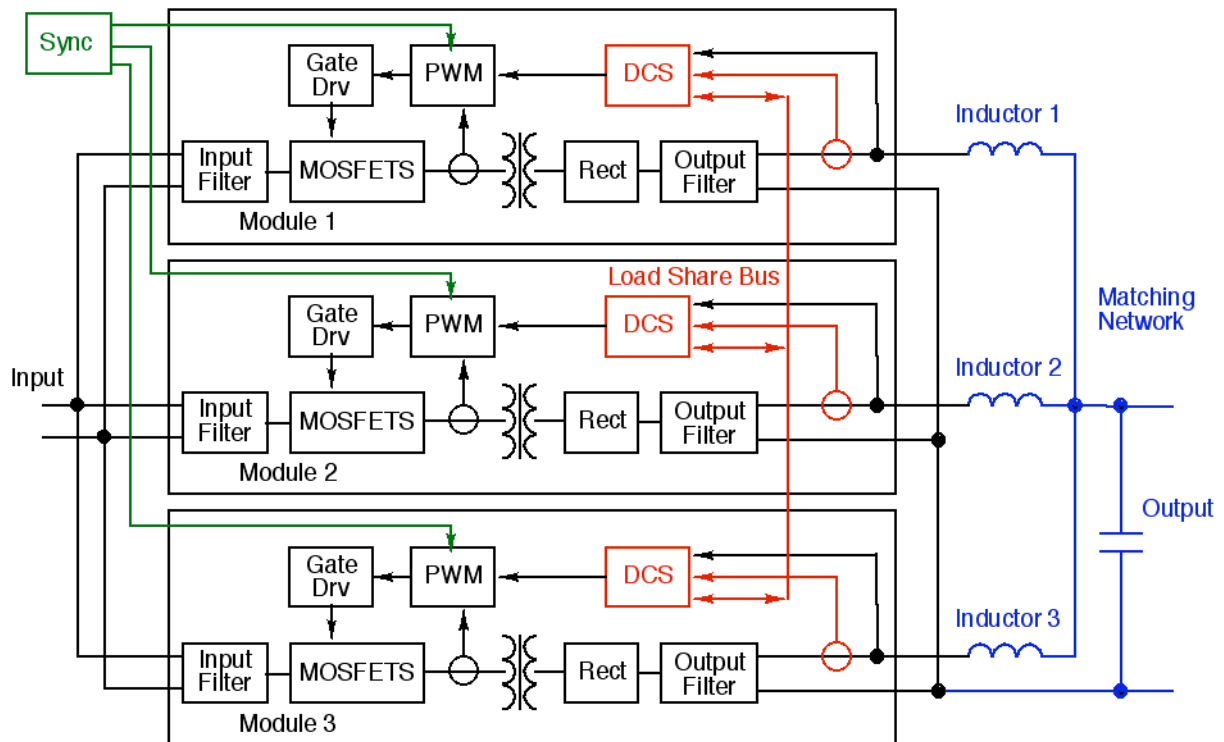
Modular architectures provide many advantages including scalability and redundancy due to the ease in adding power modules in parallel or series combinations. A modular architecture also simplifies thermal management as heat dissipation can be distributed throughout the modules. When voltage regulated power supplies are connected in parallel it is necessary to force them to share the output current supplied to the load. If a load share function is not utilized, variations in the modules can introduce large differences in the effective duty cycle of the power converter that can lead to uneven sharing of the load current limiting the maximum output current.

There are passive and active methods of implementing the load current share function. Passive methods that rely on the output impedance of the power converters are simple but can be inaccurate and difficult to implement because they require small component tolerances and circuit parasitics. Active methods yield superior performance and accuracy in exchange for a small amount of additional complexity and circuitry. The most basic way of implementing active load current sharing is a master-slave configuration in which a master module senses its output current and forces the slave modules to output the same amount of current. The disadvantage of this method is that the system is



**Figure 5. Multi-kilowatt power module efficiency**



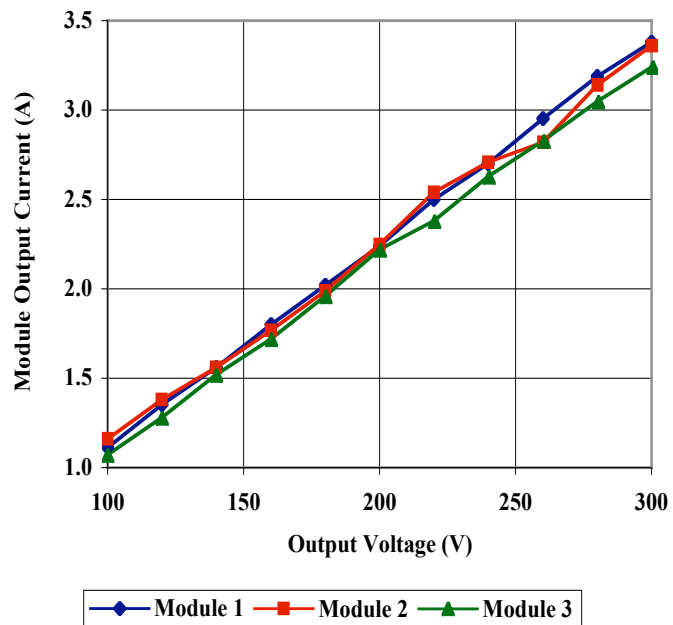


**Figure 6. Parallel module architecture block diagram**

not tolerant to master module faults. In other methods, the output currents of the modules are compared to the average current, on a common “load share bus”, and used to control the input to the error amplifiers of each module. This allows any of the modules to take control of the load share bus and act as a master. If that module fails, it can be disconnected and another module will take over the bus. This technique is called democratic current sharing (DCS) and was implemented in this design using a commercially available DCS controller.<sup>14</sup>

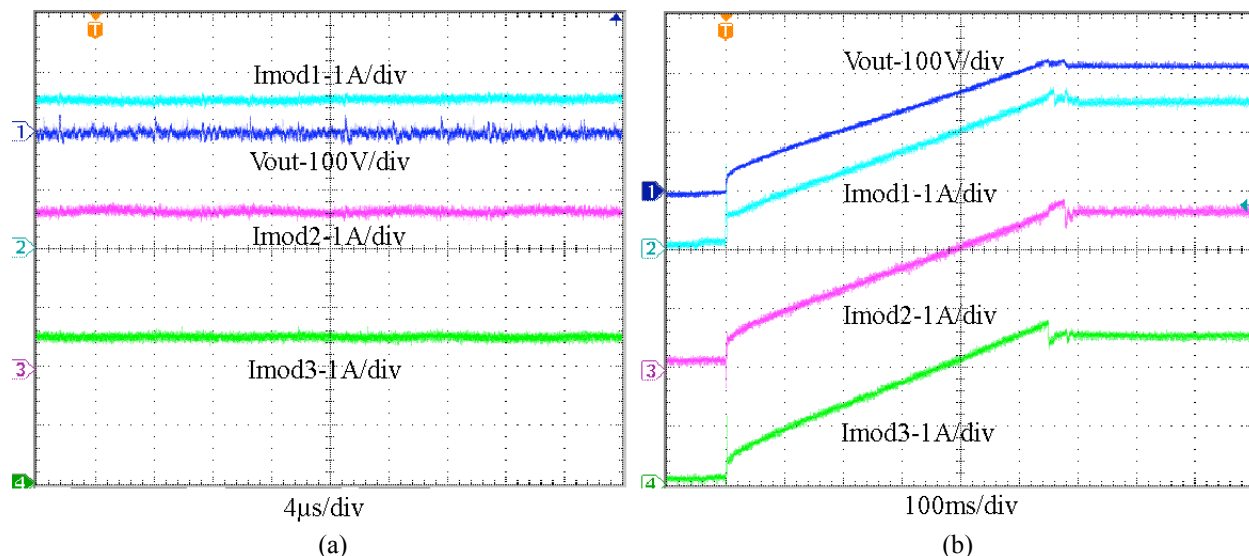
Three 1 kW modules were assembled and connected in parallel with a DCS circuit. A block diagram of the circuit configuration is shown in Figure 6. This 3 kW discharge supply was then tested using resistive load to verify load sharing performance under steady state and turn-on conditions. This is particularly important for HET PPU, because large current transients are possible as the main discharge is initiated in the thruster.

Figure 7, shows a graph of the output currents from each individual module when operating into a fixed resistive load under nominal conditions of 100 V input and 300 V output. Notice that the currents track each other very closely with a variation of no more than 4.2 percent. Similar results were obtained for other load and input conditions. The results of the turn-on test are shown in Figure 8. Figure 8a shows the individual module currents and the output voltage



**Figure 7. Load current share performance of three 1 kW modules**

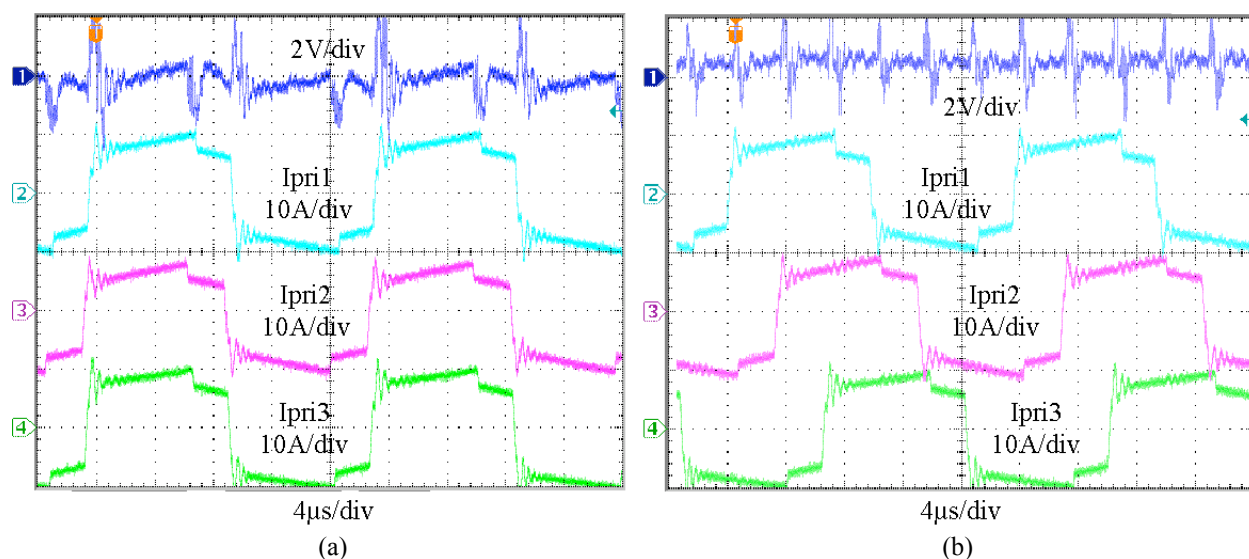
ripple for an operating condition of 100 V input and a 300 V and 7.56 A output. The individual modules output currents were 2.54, 2.57 and 2.45 A. Small oscillations can be detected in the current from interaction between the modules. Figure 8b shows the same traces taken during a turn-on. Notice that current sharing was maintained even during transient operation. This test was repeated over the entire input and output voltage ranges without significant changes in performance.



**Figure 8. Waveforms of 3 kW power supply resistive load testing showing individual module currents during (a) steady state and (b) turn-on conditions**

### B. Phase Staggering Circuit

When power modules in a modular architecture are synchronized they draw power from the input bus at exactly the same time causing high ripple currents on both input and output filters. These high input currents require larger filter inductors and capacitors to meet ripple specifications and minimize conducted emissions. Larger filters result in additional PPU mass. If the timing of the modules can be distributed or staggered throughout the switching period, peak input currents can be reduced because each module draws current at different times. The performance of the power supply is not affected.



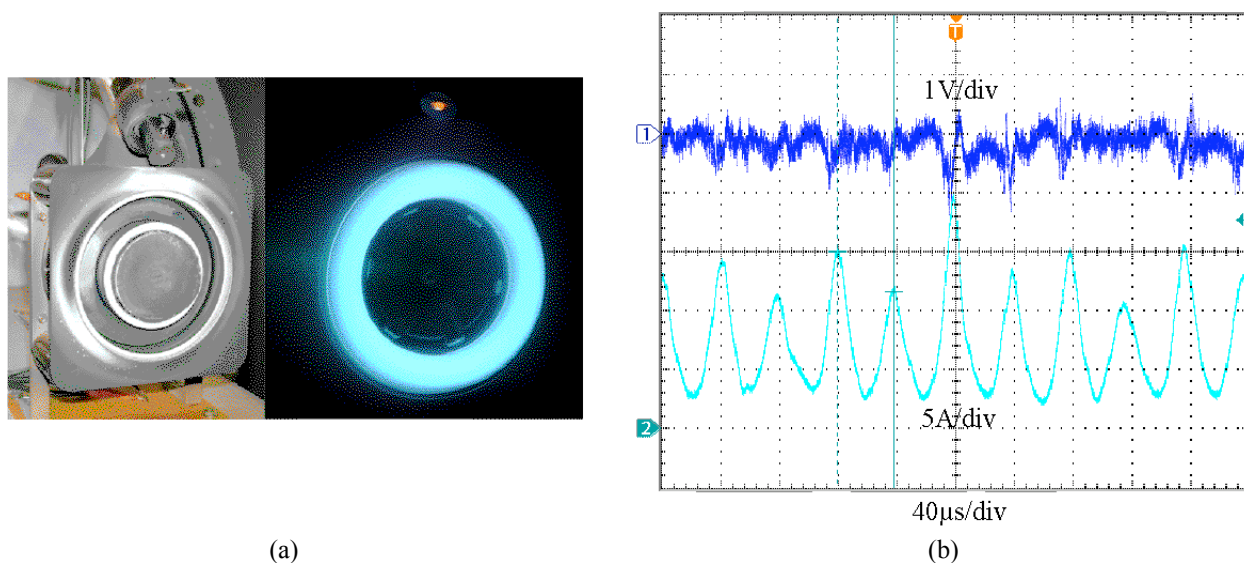
**Figure 9. Waveforms of (a) synchronized and (b) staggered power modules**

Phase staggering was implemented in the 3 kW discharge supply. It required some additional digital logic and a 4.9 MHz crystal oscillator. The master clock was fast enough to generate the narrow sync pulse required by the PWM controller and to provide sufficient timing accuracy. Scaling the circuit for additional modules would require changing the oscillator speed and additional timers or decoders depending on the total number of modules.

The effect of phase staggering is graphically shown in Figure 9. It shows the output voltage ripple of the 3 kW discharge supply and the primary current of the three modules when their phases are synchronized and staggered. The output voltage ripple was approximately 2.4 V peak-to-peak for the synchronized case and 0.8 V for the staggered case. This equates to a 67 percent reduction in output voltage ripple. This reduction in ripple can be used to reduce the size of filter components.

### C. Thruster Integration Testing

Thruster integration tests were conducted using a 3 kW-class, laboratory model NASA-120M HET. This thruster was developed several years ago by the NASA GRC Hall thruster program to serve as a test-bed for erosion diagnostics, capacitive discharge operation studies, and for investigation of the influence of channel parameters on operation. The thruster is depicted in Figure 9a.



**Figure 10. (a) NASA-120Mv2 Hall effect thruster, (b) voltage and current oscillations**

In general, HETs exhibit characteristic discharge current oscillations during operation. These are caused by inherent instabilities that occur during HET operation.<sup>15</sup> These oscillations have a fundamental frequency in the range of  $10^4$  Hz but also have components in the  $10^6$  Hz range.

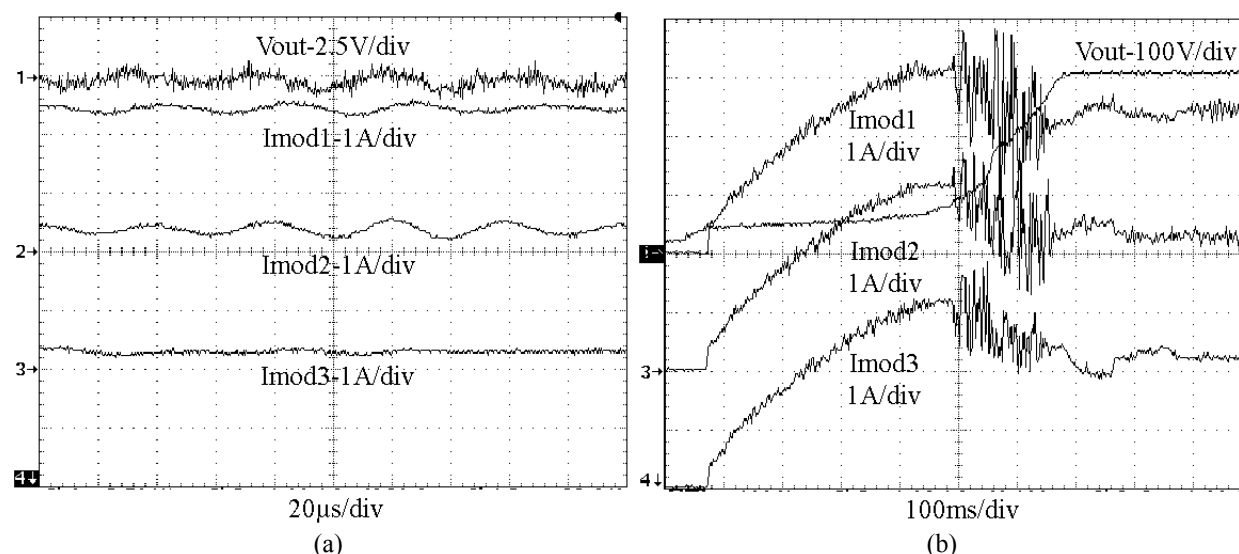
Figure 10b shows discharge voltage and current oscillations of the NASA-120M thruster operating at 300 V and 7.0 A. For this test, a laboratory power supply and a 100  $\mu$ F capacitor between the anode and cathode were used. The current was measured downstream of the capacitor, directly into the thruster anode. As seen in the oscilloscope trace, the frequency of the oscillations was approximately 26 kHz and the amplitude was in excess of 15.0 A. Integration was conducted at these non-optimized conditions as it presented a tougher challenge for the discharge power supply.

Traditionally, a “matching network” consisting of an LC low pass filter has been used between the thruster and the discharge supply. This filter supplies the thruster the ripple current it requires for start-up and steady-state operation. Also, it attenuates current oscillations into the discharge supply that can cause control instabilities and lead to power supply failure.<sup>15-16</sup> The matching network for the 3 kW discharge supply was implemented differently as shown above in Figure 6. Instead of one large bulk inductor, three smaller individual inductors were used on each output. This was done to avoid possible oscillations between the output filter capacitors in the modules due to interconnection in the experimental setup or thruster effects. The matching network used 28  $\mu$ H inductors and a 30  $\mu$ F capacitor.

The test setup used the 3 kW discharge supply to operate the main discharge and a power console to supply power to the inner and outer magnets, cathode keeper and heater. Voltage and current data were obtained using

digital multi-meters. A digital oscilloscope was used to record ripple and turn-on characteristics. Current measurements were taken at the output of the module in series with the matching network inductors. Voltage measurements were taken on the matching network capacitor.

Figure 11a shows the output voltage ripple of the 3 kW discharge supply and the individual module currents into the matching network. The operating conditions of the thruster were 300 V and 7.00 A. The individual currents on the modules were 2.43, 2.34 and 2.23 A. Thruster induced current oscillations of less than 0.50 A and voltage oscillations of approximately 1 V can be seen. However, the power supply still operated without problems. Turn-on transients are shown in Figure 11b. When the discharge voltage reached approximately 50 V, the plasma was started and discharge current flowed. Since the thruster current ramped up, it took some time to charge output filter and matching network capacitors, so low voltage operation remained for some time. Once the current leveled, the discharge voltage rapidly ramped up causing instabilities in the discharge current. Finally, the discharge voltage and currents reached steady-state levels. Notice that the output currents from the individual modules were of equal magnitude throughout the transient period as demonstrated during resistive load tests.



**Figure 11. Waveforms of 3 kW power supply during thruster integration testing showing individual module currents during (a) steady state and (b) turn-on conditions**

## V. Conclusions

A 10 kW power module for HETs was designed and tested. This module successfully employed a 20 kHz phase-shifted full-bridge converter that operated from a  $100 \pm 20$  V input and generated an output of 500 V and 20 A. Efficiencies from 94 to 96 percent were measured on a resistive load over a wide operational range. To turn this converter into a module a load current share and phase synchronization circuits were designed and tested using 1 kW modules on both resistive loads and the NASA-120v2 HET. Current sharing was better than 4.2 percent and was maintained even during turn-on conditions. The 10 kW power module and the current share and synchronization circuits will be integrated and developed into a building block for high power PPUs for thrusters like the NASA-457 HET.

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